Simulation of grid connected PM generator for wind turbines

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Abstract

This paper discusses the simulation of a power electronic converter used for grid connection of a permanent magnet generator designed for variable speed wind turbines. Previous work on the power converter is described, followed by the design parameters of the permanent magnet synchronous generator developed for wind turbines in the 10 kW range. The power electronic converter consisting of the Active Front End controlling the DC link voltage and Motion Control inverter controlling the generator, is modelled using SimPowerSystems. The configuration of the simulation model is similar to the real converter and generator. Simulation results for grid connection of the permanent magnet synchronous generator are presented followed by some conclusions.

INTRODUCTION

In the course of a research project focused on wind turbines in the 10kW range a test platform for permanent magnet (PM) generators has been assembled. Its purpose is to perform measurements on generator prototypes at varying rotation speeds and using different control strategies. The test platform is used both for research purposes as well as for educational purposes as part of the laboratory infrastructure for courses on power electronics and electrical drives for engineering students. Laboratory tests using the platform are part of a distributed course on electrical energy systems, developed by six institutes for higher engineering education and the Department of Electrical Engineering, University of Leuven, Belgium [1,2].

I. TEST PLATFORM FOR WIND TURBINE GENERATORS

In this paper a simulation model representing the test platform for PM synchronous generator is built and verified. Fig. 1 shows the electronics side of the test platform, consisting of following components:

- the power electronic converter used for grid connection of the PM synchronous generator (1);
- the power analyser for electric power measurement and calculation of generator and converter efficiency (2);
- a data acquisition system for registration of speed, torque, voltage and current measurements (3);
- the wind simulation system generating speed setpoints from wind speed measurement data (4);
- the frequency converter for variable speed control of the asynchronous motor driving gearbox and generator (5).

The machine side of the test platform located at the back consists of the drive motor, gearbox and generator (fig. 3).

The measurement results for the grid connection of the permanent magnet synchronous generator using the power electronic converter and test platform are presented in [3]. They include the efficiency curves for the generator, for the converter and total efficiency defined as ratio of the electrical power delivered to the grid to mechanical input power.

In the next sections the PM generator is described in detail, followed by the configuration and operation of the power electronic converter used for the grid connection.

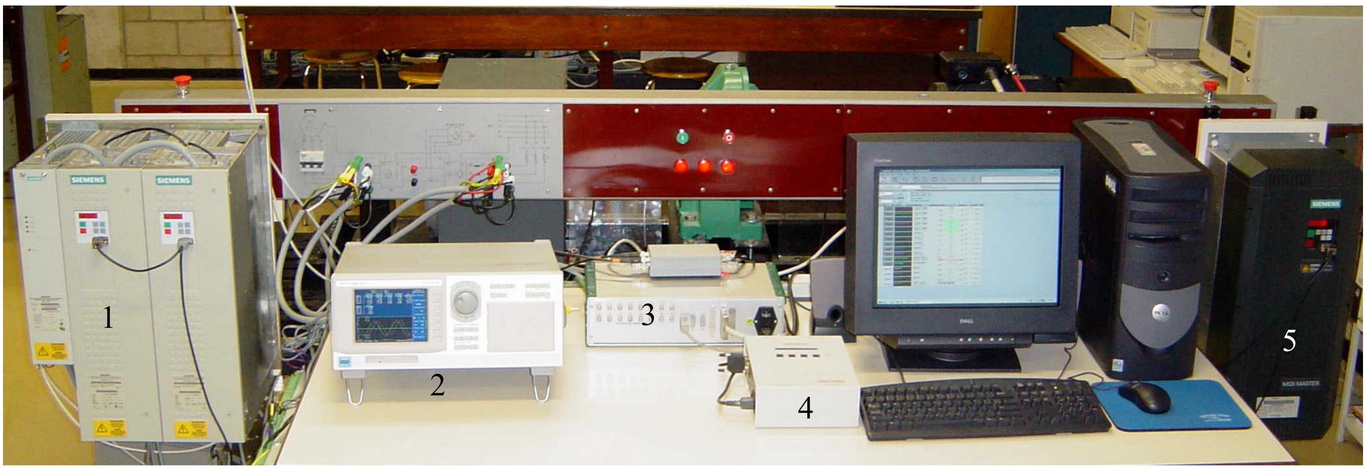

Fig. 1. Electronics side of test platform for permanent magnet synchronous generator including converter for grid connection.

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II. PM SYNCHRONOUS GENERATOR

The PM synchronous generator mounted on the test platform is a prototype (fig. 3). Its electromagnetic design has been optimised for minimum harmonic content of induced voltage and maximum efficiency using finite element calculations [4]. The generator is part of the Fortis Alize wind turbine shown in fig. 2. This generator is built up from standard motor parts in a totally enclosed housing without cooling ribs and without fan and fan cover. The frame is made of steel Fe370 and is hot zinc dipped and coated. The magnetic field is supplied by NdFeB permanent magnets with radial magnetisation. They are mounted on a pole wheel directly driven by the wind turbine blades using an internal stationary stainless steel shaft with rotational speeds up to 350 rpm. The stator is built using standard stator sheets fitted with 54 slots. The windings having especially protected class F isolation are three phase star connected. By means of a specific stator winding design, magnetic bonding of the pole wheel is nearly eliminated, such that the starting torque depends effectively on bearing friction only [5]. The rotation of the magnets induces a three phase AC voltage in the stator windings: The main design parameters of the generator and wind turbine are given in tables 1 and 2.

Fig. 2. Fortis Alize wind turbine.

TABLE 1
DESIGN PARAMETERS OF PM SYNCHRONOUS GENERATOR

Generator type	Fortis Alize II
Magnet material	NdFeB
Active length	140 mm
Air gap width	3.75 mm
Nominal speed n	300 rpm
Speed range	25 rpm – 350 rpm
Nominal torque T_{nom}	275 Nm
Maximal torque T_{max}	340 Nm
Nominal electrical power $P_{e,nom}$	7.4 kW @ 300 rpm
Maximal electrical power $P_{e,max}$	10.6 kW @ 350 rpm
Nominal line current $I_{L,nom}$	15 A
Maximal line current $I_{L,max}$	20 A
No-load voltage U_L	326 V @ 300 rpm
Number of pole pairs p	6
Nominal frequency f	30 Hz
Phase resistance R_s	1.36 Ohm
Inductance (direct) L_d	12.5 mH
Inductance (quadrature) L_q	12.5 mH

TABLE 2
SPECIFICATIONS OF FORTIS ALIZE WIND TURBINE

Rotor type	3 blade upwind with fixed pitch
Blade material	fibre glass reinforced epoxy
Blade length	3.4 m
Rotor diameter	7.0 m
Rotor area	38.5 m²
Rotor speed	25 - 350 rpm
Tip speed	max. 100 m/s
Rated output	10.0 kW

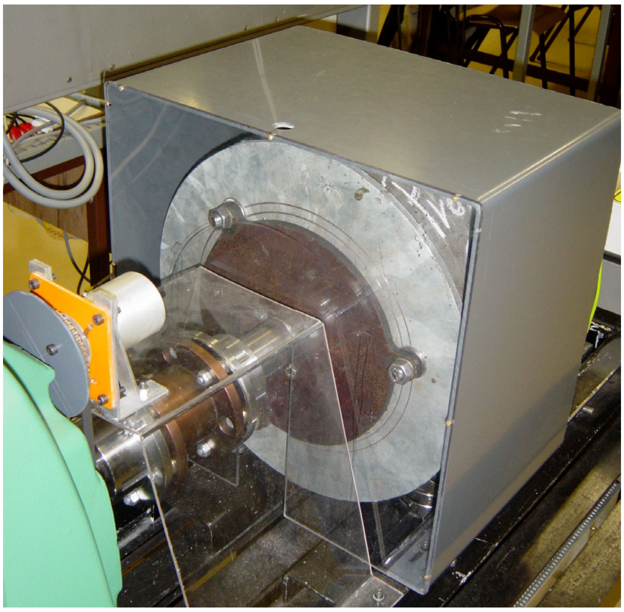

Fig. 3. PM synchronous generator mounted on test platform.

III. Converter for Grid Connection

The power electronic converter providing a grid interface for the PM synchronous generator consists of three modules: the Active Front End (AFE) supply unit, the DC link bus with braking chopper, and the Motion Control inverter.

The AFE supply unit consists of a line commutated inverter of IGBT power switches (Insulated Gate Bipolar Transistor) as shown in fig. 4. Its 'Control Unit for Supply AFE' (CUSA) board is synchronised with the power grid L1-L2-L3 using the Voltage Sensing Board (VSB). The precharging resistors R_v limit the peak currents in the supply line that occur when switching on the IGBT bridge, which temporarily acts as a rectifier charging capacitors in the DC link (C-D). The AFE inverter is available in power ranges up to 250 kW. Essential for the operation of the AFE are the reactors at the mains side (L_{AFE}, one in each supply line). They allow transfer of power from the grid to the DC bus and vice versa. The AFE reactors also act as commutating reactors reducing harmonics at current changeover between power switches and free wheeling diodes within the inverter [6]. The protective earth PE is routed through the inverter chassis to the next module.

The Motion Control inverter connects the PM synchronous machine to the DC link bus (fig. 5). It consists of a IGBT bridge inverter and a control electronics board (CUMC). The 'Control Unit Motion Control' uses vector control algorithms based on measured rotor position to control torque and speed of the synchronous permanent magnet machine. Setpoints and parameters are entered using the Parameterizing and Monitoring Unit (PMU) or the serial interface. Optional boards include the interface for the incremental encoder. The internal power supply converts the DC link voltage into 24 V supply voltage for the electronics boards.

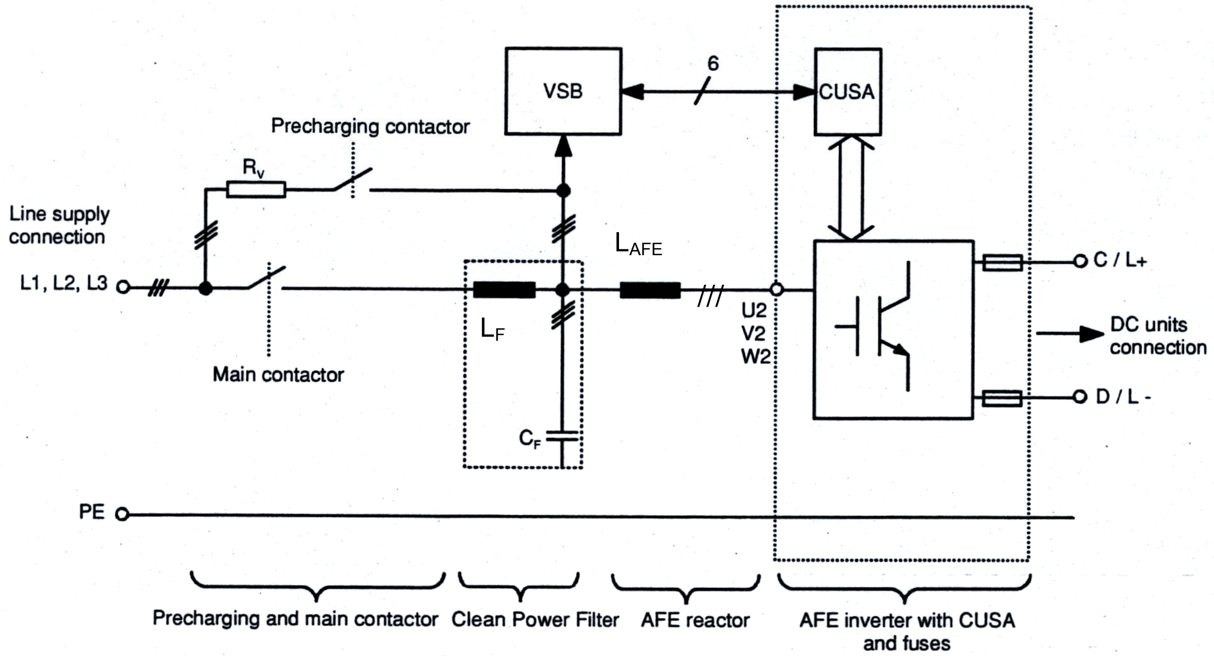

Fig. 4. Block diagram of Active Front End supply unit.

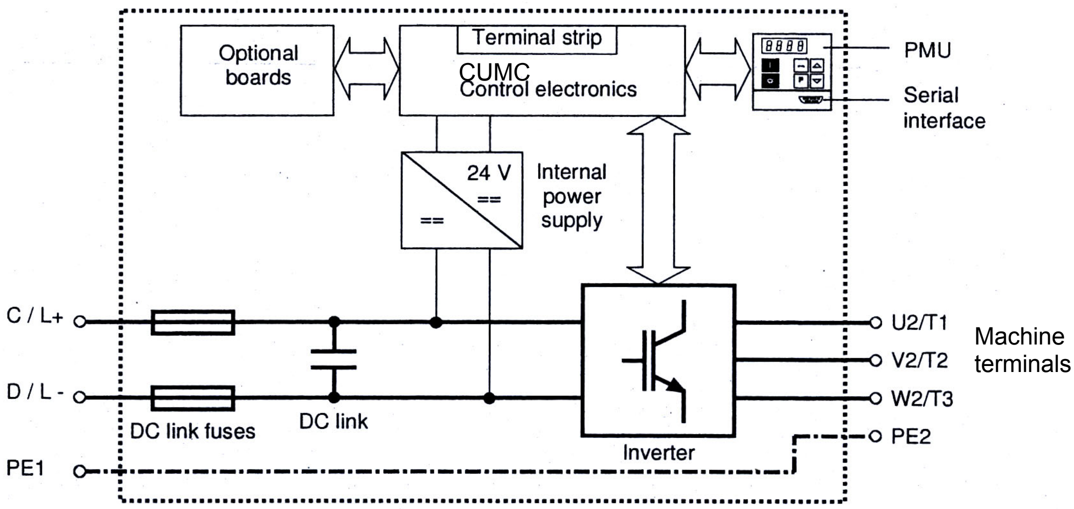

Fig. 5. Block diagram of Motion Control inverter.

IV. SIMULATION MODEL OF POWER ELECTRONIC CONVERTER AND PM GENERATOR

The model used to simulate the power electronic converter and PM Synchronous Machine is shown in fig. 6. The model is implemented using the drives library of SimPowerSystems package of Matlab-Simulink [7]. It consists of the following power electronic and electric machine blocks: the Active Front End, the Motion Control inverter and PM Synchronous Machine. In between the latter two is a Measures block for the three phase machine stator current. This is used by the Vector control block to control the torque. This block receives the torque setpoint from the Torque limiter, which passes the Setpoint input SP to the requested output Torque* after limitation between –300 Nm and 300 Nm.

Since the drive is operating in Torque control mode, the mechanical rotor speed w_m is an input for the PM Synchronous Machine block. Its value is determined by the driving motor and gearbox on the test platform that are not included in the model.

Fig. 7 shows the subsystem for the Active Front End part of the power electronic converter. The AFE inverter is connected to the grid through the inductors and current measurements. This inverter is controlled by the Bus controller to maintain a constant voltage V_{DC}. The difference between bus voltage setpoint V* and actual bus voltage V_{DC} determines the reference active current i_d. The reactive current i_q is maintained at 0 A, which means the AFE controls the power factor at the grid side λ_{grid} equal to unity [3, 8, 9].

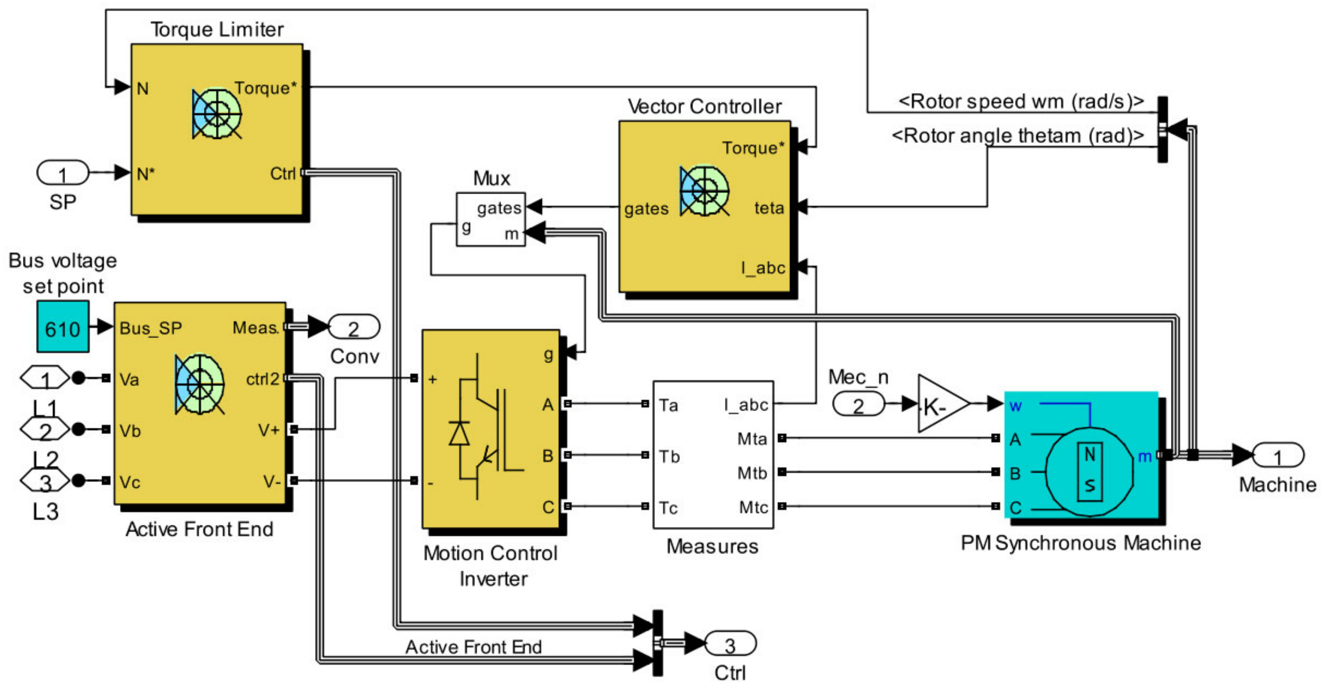

Fig. 6. Simulation model of power electronic converter and PM generator.

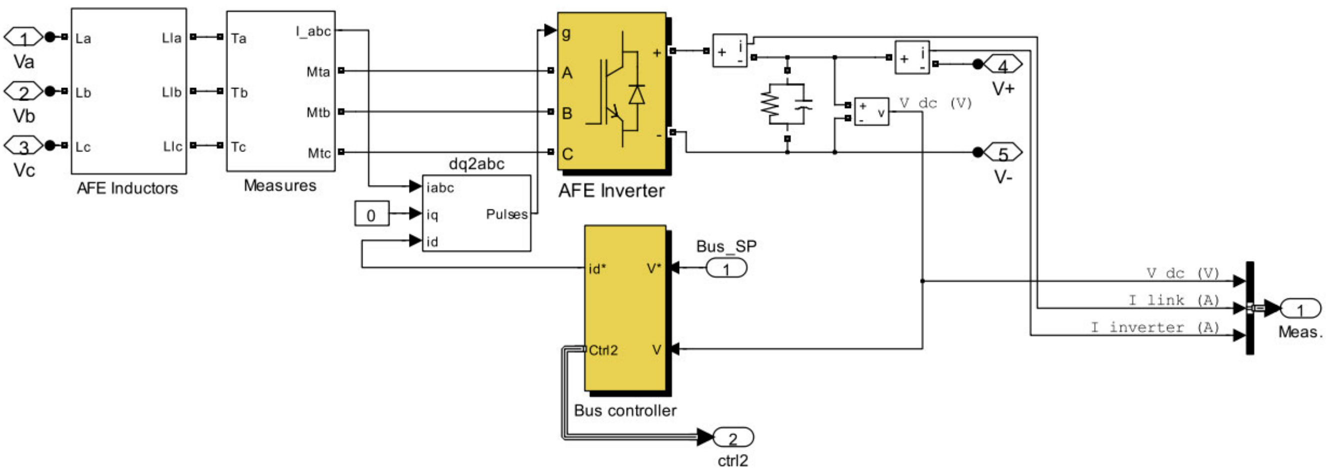

Fig. 7. Active Front End subsystem included in the model of power electronic converter.

V. SIMULATION RESULTS FOR THE GRID CONNECTION OF PM SYNCHRONOUS GENERATOR

In this section the simulation results for the grid connection of the PM synchronous generator using the simulation model described above are presented. As shown in fig. 8 the model has to be provided with following inputs: torque setpoint SP, rotation speed Mec_n and three phase voltage source L1-L2-L3 representing the grid line voltage of 400 V at 50 Hz. The output signals for the PM machine model are stator current I_a, rotor speed n and electromagnetic torque T_{em} (fig. 6, bus 1).

For the converter a selection of signals is made consisting of DC bus voltage V_{DC} , the DC link current from the Active Front End to the DC bus (I_{link}) and the active current reference I_{d_ref} at the grid side (fig. 7, bus 1 and 2). Since the Active Front End and Motion Control inverter operate at PWM frequencies of 8 kHz, it is necessary to use a 1 µs discrete time step to obtain accurate results [7]. In order to limit computation time, the total simulation time is limited to 2 s, even on a 64 bit quad core workstation.

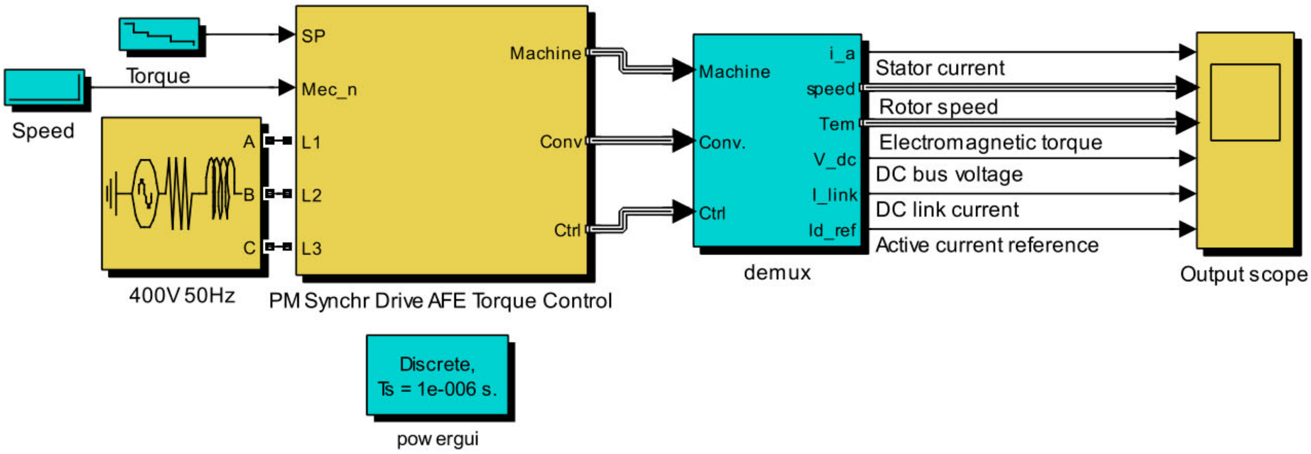

Fig. 8. Inputs and outputs for the simulation model of power electronic converter and PM synchronous machine.

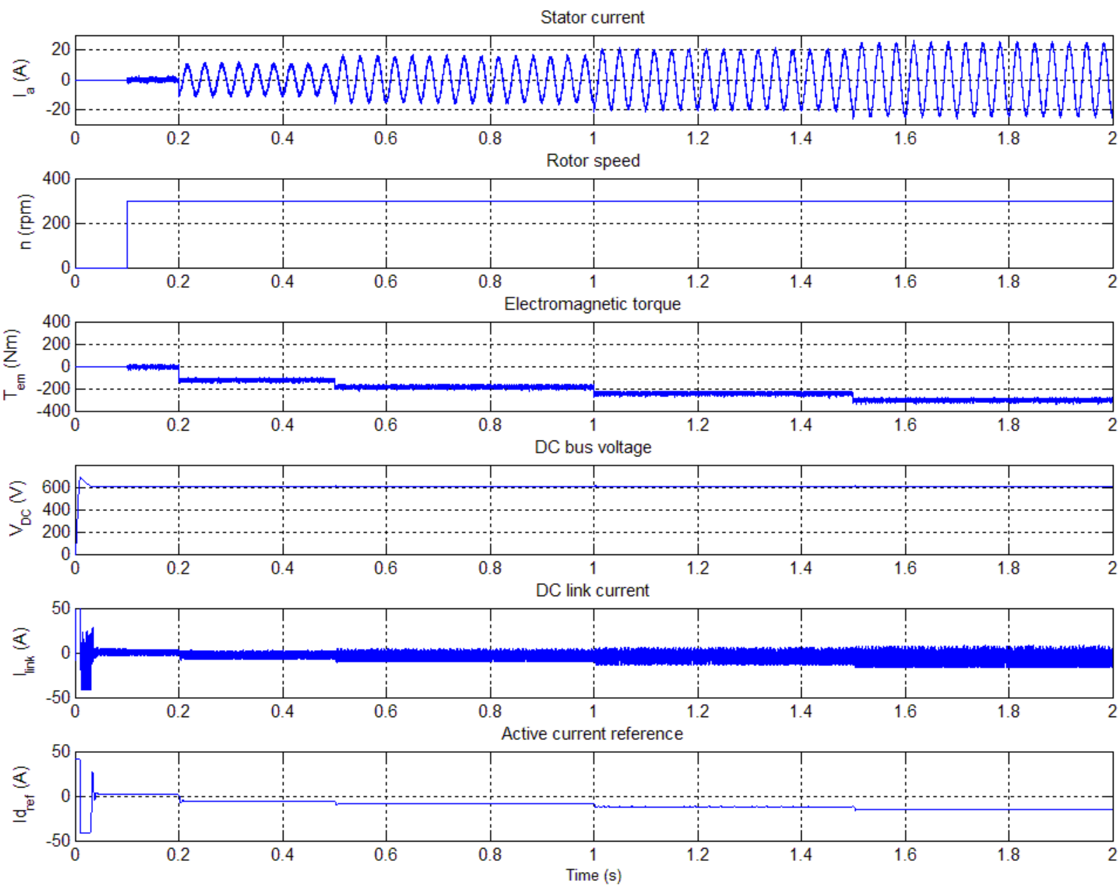

Fig. 9. Simulation results for the grid connection of the PM generator.

The simulation results are depicted in fig. 9 representing the output scope from fig. 8. The drive is started up with empty DC bus capacitors and zero speed for the first 100 ms. The Active Front End increases the DC bus voltage V_{DC} to the setpoint Bus_SP of 610 V. When charging the capacitors, the DC link current I_{link} and active current reference I_{d_ref} are initially positive followed by a negative pulse as the DC bus voltage V_{DC} temporarily overshoots the setpoint. As soon as the bus voltage V_{DC} is stabilised, the power converter is ready for use and the PM generator is allowed to run. Since the rotor speed n is determined by the external drive motor and gearbox, its dynamics are not included in the model. Also to limit the simulation time, the rotor speed n is changed instanteanously from 0 to 300 rpm at 0.1 s. The setpoint SP for the electromagnetic torque is varied in discrete steps using an input timer. As can be observed in the output scope, the electromagnetic torque T_{em} is controlled by the Motion Control inverter and Vector controller to follow the setpoint. The stator current I_a shows a stepwise increase in amplitude for each new value of the torque setpoint SP, including a phase jump as seen in the measurement results obtained from the test platform in fig. 10. This shows a change in mechanical torque T_m from 50% to 100% (-140 to -280 Nm). Since the PM machine is working in generator mode, at each increment in value of the negative torque setpoint SP and amplitude of stator current I_a, more electrical power is generated and delivered through the Motion Control inverter to the DC bus. The task of the Active Front End inverter is to maintain the DC bus voltage V_{DC} constant and feed the power from the DC bus into the grid. This can be observed in the graph of the active current reference I_{d_ref}, following the steps in electromagnetic torque T_{em}, being negative since the AFE acts as a current source towards the grid. As a consequence, the DC link current I_{link} is controlled round a negative value which means current from the DC bus to the AFE inverter in fig. 7. The output results show the basic operation of the power converter for grid connection of the PM synchronous machine and provide insight in the dependence of the different variables.

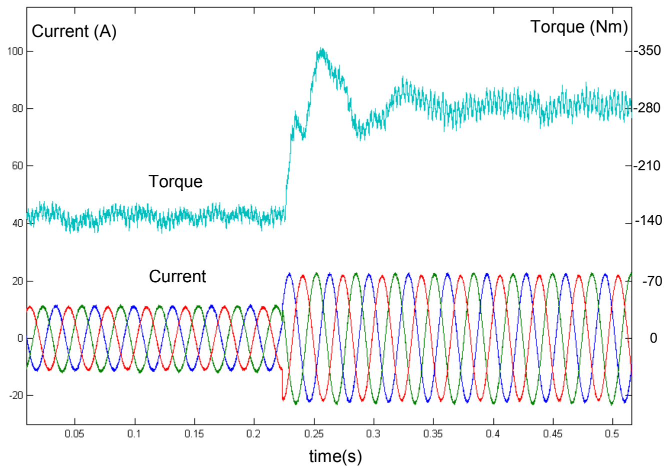

Fig. 10. Measured step response of torque control of Motion control inverter: top curve shows measured mechanical torque T_m (Nm), bottom curves show three phase stator current i_S (A).

CONCLUSIONS

The paper describes the configuration and operation of a power electronic converter used for optimal grid connection of a permanent magnet generator for variable speed wind turbines in the 10 kW range. The power electronic converter consists of an Active Front End controlling the DC link voltage and Motion Control inverter loading the generator. Using elements from the Matlab-Simulink SimPowerSystems drive library, a simulation model has been set up for the power converter and PM generator. Simulation results for the grid connection of the PM synchronous generator visualise the basic operation of the power converter and provide insight in the dependence of variables. The static analysis performed using this simulation confirms the validity of the model when compared to experimental results obtained on the test installation. The use of the model will be extended in future work towards dynamic analysis of the wind turbine operating in variable wind speed conditions and regarding grid control issues as discussed in [8, 9].

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